Reply to comment by B. Cecconi on "Spectral features of SKR observed by Cassini/RPWS: Frequency bandwidth, flux density and polarization"

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1. Introduction

[1] The main purpose of the paper by *Galopeau et al.* [2007] was to classify the spectral features of the Saturnian kilometric radiation (SKR) starting from three physical observed parameters: the frequency bandwidth, the flux density, and the polarization. We show in the present response that an unsupervised application of arbitrary automatic criteria during the data processing (such as a signal-to-noise ratio greater than 23 dB) can totally judge a weak natural emission as a background noise. As a consequence, such a situation may lead to consideration of only the data presenting a degree of circular polarization close to 100% and neglect a huge part of the data. *Galopeau et al.* [2007] considered a phenomenological aspect and gave an estimation of the Stokes parameters. This approach leads to first recognizing spectral components (flux density and bandwidth) in the frequency range from 3.5 kHz to 1200 kHz, and then deriving the Stokes parameters for each component. The Cassini/RPWS instrument provides long-lasting coverage of radio emissions at Saturn with unprecedented instrumental capabilities.

2. Importance of a Phenomenological Approach

[2] The first aim of our paper was to classify the different shapes appearing in the Saturnian kilometric emission spectrum; that led us to distinguish different components, and eventually conclude on different physical origins. Unlike *Cecconi* [2009], we believe that a phenomenological approach is sometimes still up-to-date because it concerns many subjects of investigation that remain unsolved: spectral features, polarization parameters, microscale and macroscale structures, among others, regardless of the originality of the Cassini/RPWS experiment. As examples, it is not possible to explain why the cyclotron maser instability [*Wu and Lee*, 1979] generates microstructures or macrostructures, or how the hollow cone of the microstructures and macrostructures looks. Until today, such questions can be addressed not only in the case of Saturn but also for the other magnetized planets, in particular Jupiter and the Earth.

[3] Concerning the beaming, we note confusion in *Cecconi*'s [2009] argument because the observed beaming is principally associated with the macrostructures. This is very clear because *Kurth et al.* [2005b] combined two receivers (HFR and WBR instruments) for specific SKR events, but in another paper [*Kurth et al.*, 2005a] they only used HFR measurements to produce SKR-emitted power for a period of more than four weeks. In this second case, the formed beam is associated to the macrostructure (mainly the component B of *Galopeau et al.* [2007]). Therefore it is not possible to say exactly how the beaming of the microstructures looks, or to extrapolate from the second paper.

3. SKR Spectrum Classification and Subcomponents

[4] While we actually took the quasi-thermal noise (QT) contribution into account in our automatic, adaptative background substraction procedure, it has been well known since Voyager epoch that a specific, low-frequency component, different from SKR, does exist at Saturn [cf. *Kaiser et al.*, 1984]. The A component was not much studied using the Voyager/Planetary Radio Astronomy data set, due to its scarce frequency coverage below 100 kHz; however, see *Warwick et al.* [1981]. Rather, it was investigated using the Voyager Plasma Wave Science instrument [e.g., *Kurth et al.*, 1982; *Gurnett et al.*, 1981]. Interchangeably termed as a "trapped continuum," an "escaping continuum," or "narrow band electromagnetic radiation" [*Kaiser et al.*, 1984], the origin of this component is not fully understood. An explanation by conversion of intense electrostatic waves into electromagnetic radiation on density gradients in the inner magnetosphere was suggested [*Gurnett et al.*, 1983], but is still subject to investigation.

[5] The extended coverage of the unified Cassini/RPWS instrument offers a much better opportunity to study the A component in detail. Figure 1 shows a spectrogram example

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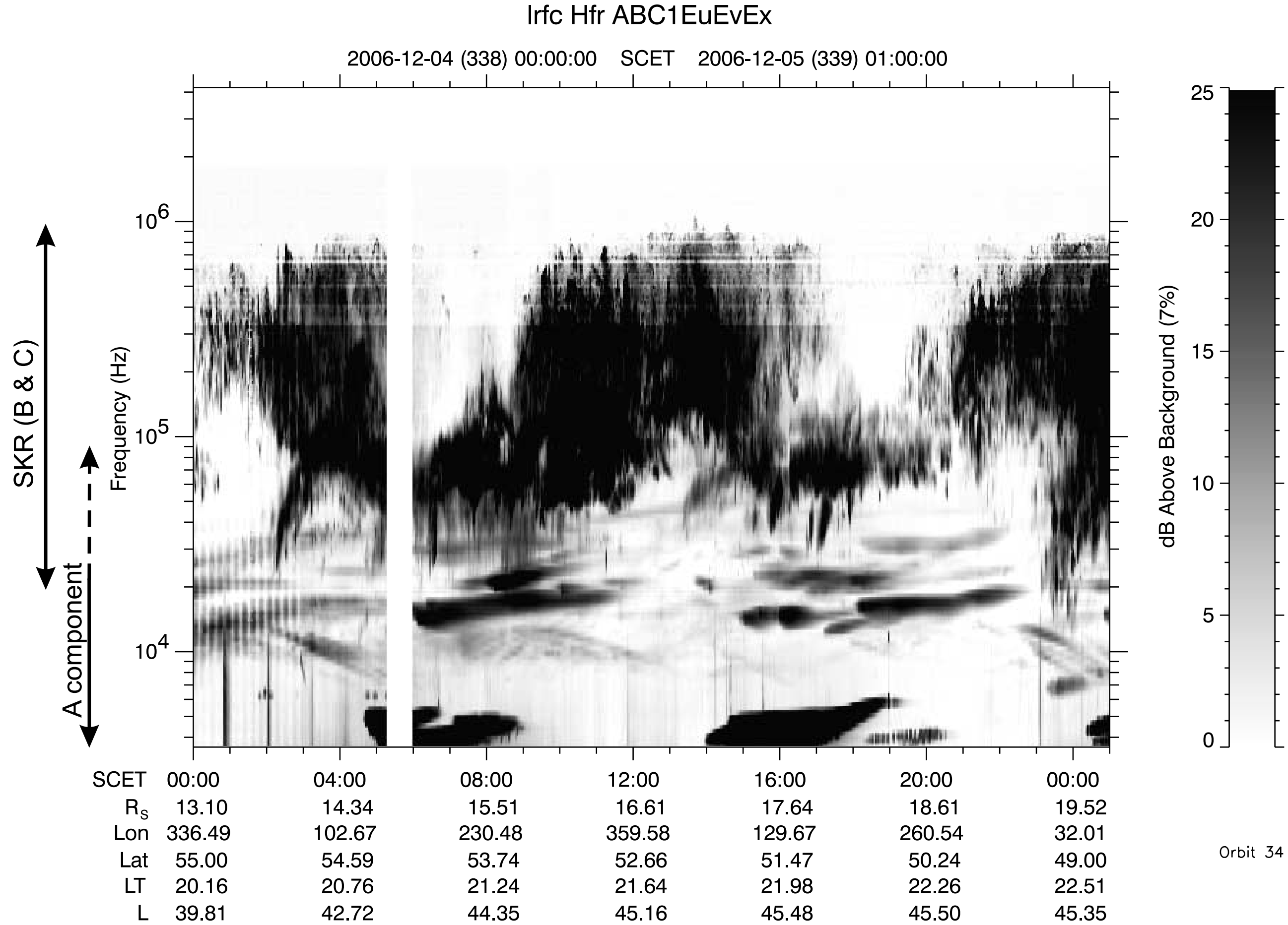

Figure 1. Example of overlapping A component and B and C components. The A component exhibits a complex dynamic spectrum, different from the SKR one, and cannot be mixed up with quasi-thermal noise or any other kind of broadband local noise.

from the Cassini/RPWS data set, in which component A is clearly disentangled from the normal SKR component, with a well-characterized and complex time-frequency morphology. As stated by *Galopeau et al.* [2007], the overall spectrum slope decreases from lower to higher frequency (at the difference of components B and C) and may or may not overlap the SKR spectral band. The polarization is well measurable and complex. It is certainly appealing to use direction finding and polarization capabilities of the RPWS instrument for a better understanding of this component.

[6] Regarding our identification of an additional component C, as some kind of detached high-frequency part of the SKR component, we note that radio astronomy instruments aboard Voyager and Cassini used different radio spectrum sampling schemes (linear and logarithmic frequency sampling), which might result in different classifications, when only based on spectrogram morphology.

4. SKR Elliptical Polarization

[7] *Galopeau et al.* [2007] addressed the problem of evaluating the actual accuracy of available SKR polarization measurements and the way to definitively rule out the presence of any linear polarization component in Saturn's radio emissions, already questioned by *Ortega-Molina and Lecacheux* [1990] from their analysis of Voyager data. Since the PRA radio astronomy instrument aboard Voyager did not have the capability of performing a full polarization analysis, a confirmation of the latter analysis should obviously be carried out by using the Cassini/RPWS experiment.

[8] This suggestion requires the availability of an accurate and consistent statistical mathematical model of the RPWS radio astronomy response in order to get reliable confidence intervals on obtained estimates of Stokes parameters. It also implies the use of such a model with a statistically representative subset of the SKR data in order not to have biased data from various observing effects (intensity threshold, special geometry, multiple sources in antenna beam, etc). We think that such an analysis is still not available.

4.1. Observational Conditions

[9] *Cecconi* [2009] shows dynamic spectra of SKR (see his Figures 1 and 3) principally based on methods described in two papers: *Zarka et al.* [2004] and *Cecconi and Zarka* [2005]. With regard to this matter, we have used a similar approach in the data processing. A. Lecacheux (Solar type III burst analysis with Cassini/RPWS: Lessons for Stereo, report presented at Solar Orbiter and Stereo Meeting, Graz, Austria, 28–29 November 2005) showed the way that can

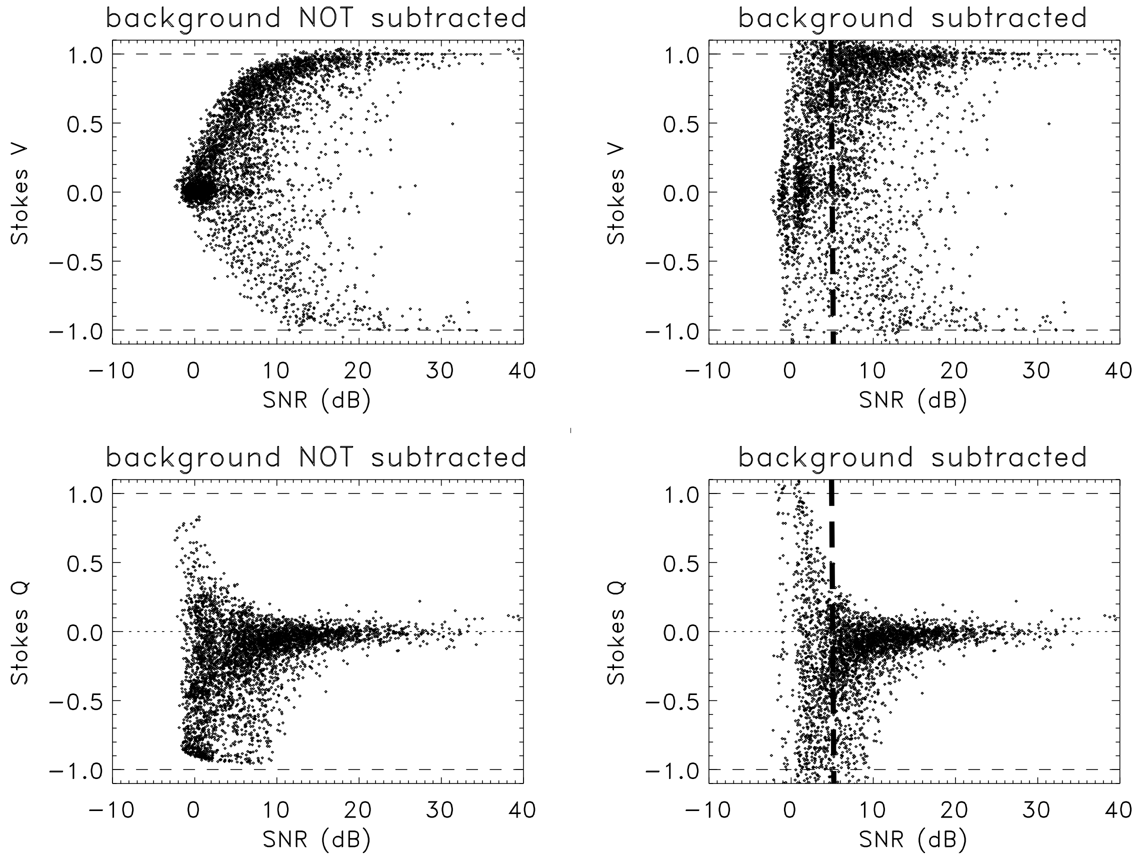

Figure 2. Comparison of the "SNR biasing effect" (see text) (left) before and (right) after background subtraction. The processed data correspond to the same period (2006-01-09) as Figure 4 of *Cecconi* [2009]. After appropriate subtraction of the background, the empirical threshold for selecting data is, in this case, about 5 dB above background, at a much lower level than the 23 dB threshold quoted by *Cecconi* [2009].

be used to derive the Stokes parameters in the case of the Stereo/SWAVE experiment, which is based on the same concept as the Cassini/RPWS experiment. However, the basic original ideas were reported by *Lecacheux* [1978], *Lecacheux et al.* [1979], and A. Lecacheux (Two antenna direction finding with purely circular polarization, report presented at RPWS Team Meeting, University of Iowa, Iowa City, 22–24 May 2000). This means that the methods are actually not so different, but the conditions to fix some observational parameters like the signal-to-noise ratio (SNR) or the assumption on the source location seem not to be similar. However, a first paper published by *Cecconi et al.* [2006] has indirectly addressed this real problem. The authors considered the polarization measurements for specific arbitrary frequency bands (LF: 10–100 kHz, MF: 100–325 kHz, HF: 325–1200 kHz), and for a period of more than 10 days. They used two criteria for the data processing: (1) SNR > 20 dB on both antennas and (2) a geometrical selection (as described by *Cecconi and Zarka* [2005]) such that the elevation of Saturn above the plane formed by the x dipole and w monopole antennas is larger than 20°. The real difficulty appears when the authors gave the selected data to the total data ratio for each band: 0.3% for LF, 0.02% for MF, and 0.005% for HF. Thus two remarks come into sight: (1) why is the selection more restrictive at high than at low frequencies, and (2) how does a dynamic spectrum look after this very restricted selection? A clearer response to the previous questions will need further investigation.

[10] Furthermore, the main published works about SKR polarization is limited to two parameters (the intensity and the degree of circular polarization) or a very specific event where the four Stokes parameters are given but more than 60% of the observed dynamic spectrum is neglected. Of course the source location of the SKR totally depends on the direction-finding technique, discussed in terms of statistical significance for the first time by *Ladreiter et al.* [1994], which is based implicitly on unbiased measurements of the full Stokes parameters.

4.2. Accuracy on Polarization Parameters

[11] *Cecconi* [2009] affirms that the ultimate recipe was provided by *Cecconi and Zarka* [2005], for which needed accuracy can only be obtained for interference-free, very intense events (SNR > 23 dB, which is more than 100 times the background level) in limited arrival directions (less than 3π sr) with respect to the antennas. A blind application of these rules obviously limits the usable data set to a few percents of the available data.

[12] As an example, let us consider Figure 4 of *Cecconi* [2009], in which calculated Q (linear degree) and V (circular

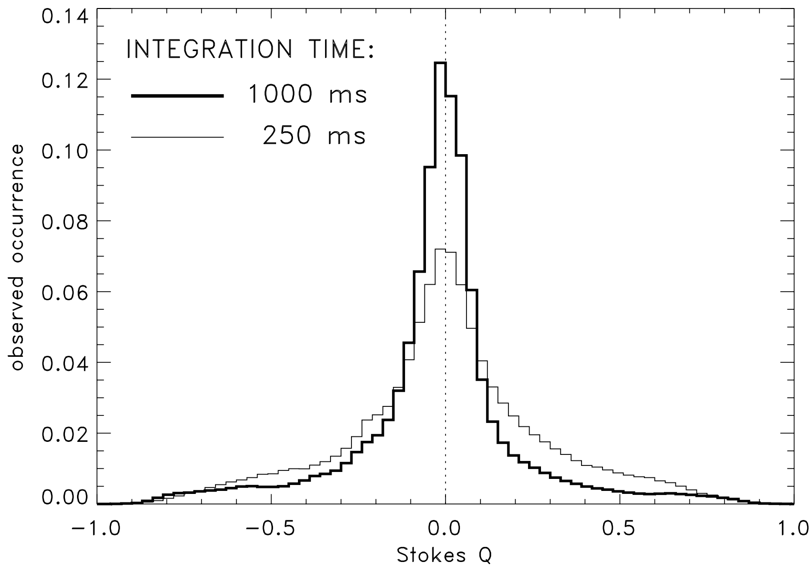

Figure 3. Histograms of Stokes Q parameter (linear polarization) for two different tunings of RPWS receiver (integration times of 1000 ms and 250 ms) and the same data as in Figure 2. The half amplitude histogram widths appear to be proportional to the noise fluctuation levels or, equivalently, proportional to the square root of the integration times.

degree) Stokes parameters are displayed in function of the logarithm of signal intensity above the background. We have used a subset of the same data (9 January 2006) in plotting our Figure 2, for comparison. Likely, there is a mix-up in *Cecconi*'s [2009] analysis between the effect due to relative intensities of signal and background (SNR), and the effect due to noise fluctuations, inherent to any radiometric measurement and proportional to the square root of the sampling time-frequency product.

[13] The apparent bias due to SNR (shown in the two top plots of *Cecconi*'s [2009] Figure 4 or in the two left plots of our Figure 2) can easily be removed, for a large part, by correctly subtracting the background level as displayed in the two right plots. The accuracy of the background determination is mainly limited by the following factors: (1) the digital signal quantization, (2) the presence of low-level, undetected interference, (3) the variations of local plasma noises, depending on local plasma, and (4) the distribution of the nonuniform galactic brightness, depending on spacecraft attitude. As shown in the right plots of Figure 2, an intensity threshold of only a few dB (about 5 dB in the studied case) is enough to remove any bias: it is far less than the quoted "23 dB criterion" of *Cecconi and Zarka* [2005] and allows, of course, the quantitative study of a much larger part of the observed events.

[14] On the other hand, the scatter of calculated, instantaneous Stokes parameter values, which is the actual limitation in wave direction and polarization retrieval, is nearly independent of SNR but depends on the noise fluctuation level. It can be shown that Stokes parameter variances are proportional to the spectrometer time-frequency product, as illustrated by Figure 3, in which histograms of calculated Q (for the same data as before) are displayed for the two used values of the RPWS receiver time constant. This demonstrates unambiguously that a given accuracy, say 1° in direction and 10% in polarization retrieval, can only be achieved after some time integration or equivalently frequency channel summing up, and is only marginally dependent on SNR. For example, in Figure 3, the standard deviation on Q is approximately 10% and 20% for time integration of 1000 ms and 250 ms, respectively. By averaging over a larger number of samples (say during 10 minutes and correspondingly ~100 samples), the 1% accuracy level can be reached, in principle. Of course, such a time/frequency integration implies additional assumptions on signal stationarity, which cannot, a priori, be guaranteed.

[15] The lower panel of *Cecconi*'s [2009] Figure 4 introduces another entirely different fact, for which any published serious quantitative treatment is still missing. When only a pair of wire antennas (considered as acting as short electric dipoles) is used, its polarization response is mainly dependent on the received wave-direction-angle θ to the antenna normal. The polarization response is basically circular along the normal, and linear within the antenna plane. Given a direction of arrival, the polarization, as defined by four Stokes parameters or, equivalently, by the four covariance components of the wave electric field, is a linear function of the measured antenna output covariance directly provided by the RPWS receiver. This linear function is defined by a square 4×4 matrix, which is highly ill-conditioned; that is to say its condition number varies as $1/\cos^4\theta$, and the matrix even degenerates at $\theta = \pi/2$. As a consequence, the accuracy on polarization parameters decreases rapidly when θ approaches $\pi/2$, to an extent that depends on various other quantities, mainly the noise fluctuations (see above) and the assumptions made on arrival direction and source brightness distribution. So, the "Cecconi 20° rule" on polarization is somewhat arbitrary and should be refined accordingly.

[16] Since the RPWS antenna system actually contains three monopoles, which can be combined in two pairs alternatively, the right strategy for polarization retrieval

should use this full combination, by which only a small solid angle around the *Z* antenna, the antenna common to each antenna pair, would have to be avoided. Unfortunately, during the two first years of Saturn's tour, on which the *Galopeau et al.* [2007] statistical study was mainly based, the RPWS instrument was mainly operated in a one antenna pair configuration. New data are now available, with a substantial amount of two antenna pairs data: our study should be extended and revised accordingly.

5. Conclusion

[17] From this response to *Cecconi* [2009], several points emerge. The first one concerns a conceptual method to determine Stokes parameters from actual measurements, and we have addressed the main problem about the way to select the supposedly correct polarization measurements. Very constricted conditions compel us to neglect 60% of the observed SKR where the polarization is far from circular. In this case one has to explain the meaning of the large part of data that were not selected. The response to this question can be given by the phenomenological approach which is the second important point of our answer. In our investigation, we first began to study the different SKR spectral components using a manual technique, i.e., looking directly at the dynamic spectra processed with the method described by *Galopeau et al.* [2007, section 2.2]. We dealt with three components, and then decided to derive the corresponding Stokes parameters. The reported three components are real, and some new investigations confirmed the presence of the particular spectral shape in the lower spectrum of the observed SKR. Two independent analyses performed by *Boudjada et al.* [2007] and *Louarn et al.* [2007] have confirmed the presence of a narrow-band spectral emission using WBR and HFR instruments, respectively. These two previous investigations principally took into consideration the phenomenology of the SKR emission.

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